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Dynamic response of composite structures underwater

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MONTEREY, CALIFORNIA

THESIS

DYNAMIC RESPONSE OF COMPOSITE STRUCTURES UNDERWATER

by

Jacob E. Russell

September 2013

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13. ABSTRACT (maximum 200 words)

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To better understand the responses at varying locations due to fluid-structure interaction, a composite plate was made with several strain gages affixed in one quadrant. The plate was then subjected to increasing impact forces while suspended in air, as well as being submerged in water. Additionally, a beam sample was also tested under the same conditions, with strain gages being affixed in-line with the impact rod.

By comparing the strain gage responses between the open air and submerged samples, a better understanding of the magnitude of the fluid structure interaction is achieved, identifying critical locations in the samples that are most likely to fail.

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DYNAMIC RESPONSE OF COMPOSITE STRUCTURES UNDERWATER

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Submitted in partial fulfillment of the
requirements for the degree of

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LIST OF ACRONYMS AND ABBREVIATIONS

FSI	Fluid Structure Interaction
SG	Strain Gage

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I. INTRODUCTION

A. BACKGROUND

Composite materials have been utilized for hundreds of years, dating as far back as the 1st Dynasty in Ancient Egypt, about 3,000 BC, when it is credited with inventing paper made from papyrus. Through the years, composite materials have been used in making houses (straw reinforcing mud, plywood), weaponry and armor (layered swords), high-rise buildings (rebar reinforcing concrete), and automobiles (body panels, seats, etc) [1]. The Navy has worked with composite materials and has successfully built small hulled patrol crafts (less than 15 m in length) as far back as in the 1940s. Further advancements in the composite material technology allowed larger hulled vessels to be built. The mine countermeasure ships, with a length of 68.3 m, were built in the 1980s. These ships have a fiberglass reinforced wood hull. This minimized the amount of steel that was used in the ship, which allowed it to perform its mission without triggering magnetic mines. As a side effect, the ship's hull was also lighter than a similar hull made of steel. The ability to apply composite materials to larger hulls is being actively pursued, with the LPD-17 San Antonio class featuring two fully enclosed radar and antenna masts, of which the enclosures are made of composite materials.

A composite material experiences low velocity impacts throughout its service life, and even during the manufacturing process [2]. These impacts are of particular interest because they may not always be detectable or felt by the rest of the system that the laminate is built into. There are several definitions for what constitutes a low velocity impact with regards to a composite material. Peter Sjoblom defines a low velocity impact as

> …an impact velocity low enough to justify a static analysis of the response of the structure. For stiff light structures with a high resonance frequency, the upper limit may be on the order of tens of m/s. For very flexible heavy structures it may be on the order of cm/s or less.[3]

Conversely, Liu and Malvern [4] use the amount of damage that the sample experiences. An impact is low velocity if there is only delamination and matrix cracking, while high velocity results in full penetration. This is more dependent on the strength of the material and epoxy; however it gives a clear distinction of the visual effects of varying impact speeds.

Another concern is fluid structure interaction (FSI). FSI, as it relates to this study, is the interaction of a deformable plate in a surrounding medium (air, water, etc.). A plate can be designed to withstand impact forces, deflection, corrosion, and any other number of design specifications; however, if the interaction between the plate and its surrounding media is not considered in the design process, failure can occur due to a non-conservative design.

Air has a density of about 1.2 kg/m^3 (at sea level and 20°C), whereas water has a density of 998.2 kg/m^3 (with the same conditions as air). This higher density can affect the response of a composite plate to an impact, thus potentially creating a situation in which a design which may work perfectly for an aircraft, would fail for a submersible.

It was developed, in a thesis published by Angela Owens [5]. , that the FSI for a water-backed plate significantly affects the magnitude and frequency of the strain of a composite plate. She proved that due to the added mass effect, the natural frequencies for a water-backed plate are lower than those for a dry plate. She concluded that the added mass effect of water increased the impact force by nearly 50% and "…a 20%-50% increase in strain, and a decrease of more than half in frequency for composites submerged in water" [5]. This is a significant increase and illustrates the importance of effectively predicting the response of a submerged composite component because it will respond differently than a similar component surrounded by air.

B. OBJECTIVES

The purpose of this study is to better understand the fluid structure interaction of a flat plate or a beam, suspended in water, to a low velocity impact, and how that compares to a plate that is suspended in air. By utilizing strain gages, the responses at different locations can be examined and compared. Conclusions can then be drawn about the effects that submerging a laminate in water has.

A beam computer analysis will be designed and compared to the experimental test data. This will aid in the verifying the data and ensure that it can be modeled.

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II. EXPERIMENTAL TECHNIQUE

A. REQUIRED MATERIALS

1. E-Glass

For the purpose of this study, a six oz, plain weave, E-glass was used. The thickness of this material was nominally 0.236 mm [6]. When wetted, the material was transparent, which allowed for a quick visual inspection for dry spots that could lead to inconsistent data. The tighter weave pattern was utilized because it had shown more consistent data between samples than a coarser weave pattern [7].

2. Resin and Hardener

A M1002 resin/237 hardener laminating epoxy made by PRO-SET was used for laminating the E-glass. The 237 hardener allows for a nominal open time of 4.5-6 hours at 22.2°C, with a pot life of 80 minutes. Actual pot life for this study was typically 45-60 minutes. All mixtures were prepared in accordance with the PRO-SET targeted weight ratio of 100:24 (the acceptable range is 100:26.1–100:20.9) [5]. The samples were not fully cured as there was no access to an oven large enough to cure the plate samples, all samples were thus cured at room temperature (nominally 22.2°C) for uniformity. As the intent of this study was to compare the response between samples suspended in air versus samples suspended in water, the strength of the material was not a deciding factor for material selection. Table 1 shows the physical properties that are given by PRO-SET for the epoxy with a 60°C (140°F) cure temperature.

Table 1. M1002 Resin/237 Hardener Laminating Epoxy Properties (PRO-SET)

Physical Property	Test Method	Cure Schedule		
		RT x 15 hr + 140°F x 8 hr	RT x 15 hr + 140°F x 16 hr	RT x 15 hr + 180°F x 8 hr
Hardness (Shore D)	ASTM D-2240	83	83	83
Compression Yield (psi)	ASTM D-695	14,133	14,093	13,916
Tensile Strength (psi)	ASTM D-638	10,039	10,069	9,588
Tensile Elongation (%)	ASTM D-638	5.5	4.6	5.7
Tensile Modulus (psi)	ASTM D-638	4.33E+05	4.21E+05	3.94E+05
Flexural Strength (psi)	ASTM D-790	18,767	18,466	17,685
Flexural Modulus (psi)	ASTM D-790	5.55E+05	5.46E+05	5.14E+05
Heat Deflection Temperature (HDT) (°F)	ASTM D-648	170.0 °F	169.0 °F	189.0 °F
Onset of Tg by DSC (°F) **		175.8 °F	180.3 °F	197.2 °F
Ultimate Tg by DSC (°F) **		197.2 °F	197.2 °F	197.2 °F
Izod Impact, notched (Ft-lb/in)	ASTM D-256	0.701	0.698	0.546

3. Tools

The tools required to cut and lay-up the various samples include:

- Tape measure
- Cutting wheel
- Paint roller with foam pad
- Bubble buster
- Squeegee
- Scissors
- Sealant tape
- Release Wax
- Gloves
- Perforated Release Film
- Foam pad
- Mixing stick
- Vacuum bag
- Vacuum pump
- Vacuum hose

- Spiral wrap
- Resin trap
- Vacuum Gage
- Glass Foundation

B. COMPOSITE FABRICATION

1. Plate Sample Procedure

a. Step 1: Cutting Material

Cut each layer of E-glass, ensuring the weave is not damaged or misaligned. Using a straight edge and a cutting wheel is highly recommended. Figure 3 shows a mat with a 2.54 cm rectangular pattern stenciled on it being used. This allowed a visual inspection to ensure each layer was square, and the weave of the E-glass was not disturbed. Using the same method, cut the perforated release film, foam, and vacuum bag. Ensure the peel ply and foam are slightly larger than the sample (one in larger on each side) and the vacuum bag will be large enough to cover the entire rectangle you will make in step 2.

Figure 1. Cutting Layers of E-glass

b. Step 2: Preparing Glass Surface

Cut the sealant tape into long strips, and place onto the glass foundation in a rectangular shape. This rectangle should be large enough to build your sample within the sealant tape, with a several centimeters on each side of space to allow for excess epoxy to squeegee off the sample. Do not remove to tape backing on the sealant tape until after the sample is built and ready to have a vacuum applied.

Wax the inside of the area just created by the sealant tape. We used Meguiars Mirror Glaze 88. This created a haze on the glass, which allowed for a quick visual inspection of any glass surface that did not have wax on it.

c. Step 3: Mix Epoxy

Once the surface is prepared and all the sample layers have been cut, mix the hardener and resin together using the scale. For Sample 13, which was a 48.26 cm x 48.26 cm sample that had 12 layers, we used 503g of M1002 resin and 120.7g of 237 hardener. This mixture had weight ratio of 100:23.996, which is the target weight ratio as advertised by PRO-SET.

$$\frac{503g}{100\,parts} = 5.03\frac{g}{part} \tag{0.1}$$

$$\frac{120.7g}{5.03\frac{g}{part}} = 23.996\,parts \tag{0.2}$$

Thoroughly mix the resin and hardener using a mixing stick, mixing for approximately five minutes.

Table 2. Beam and Plate Sample Compositions

Sample	Room Temp (°F)	Layers	Width (cm)	Length (cm)	M1002 Resin (gram)	237 Hardener (gram)	Vacuum (in.Hg)	Vacuum Time (min)
2	73	18	15.24	50.80	412.7	98.6	30+	60
10	73	10	48.26	48.26	625	150	10	20
12	76	10	48.26	48.26	625	150.2	10	5
13	75	10	48.26	48.26	503	120.7	10	5

d. Step 4: Lay-Up

Begin by coating the waxed glass surface with enough resin to cover the general area of your sample. The epoxy is spread using the roller with the foam pad. Once a base of epoxy is created, begin laying layers of E-glass down. Typically, we would lay one layer at a time and, using the bubble buster, smooth the sample and eliminate any air bubbles. Using pressure on the bubble buster, we were able to thoroughly wet each layer and ensure a tight packing of the prior layers. If there are white areas, this means the layer is not fully wet, and more epoxy should be added. Roll the epoxy using the foam roller and then remove air pockets with the bubble buster.

Add each subsequent layer until the sample is built up. Any excess epoxy should be on top with each layer of E-glass tightly packed with no air pockets. Visually verify this by sliding the glass off the bench look for discoloration in the sample. Any discoloration means a dry area and more epoxy should be added. Figure 4 shows the uniformity the sample should have. Notice the backing is still on the sealant tape to prevent epoxy from getting on the tape and preventing a good vacuum. Once the sample is uniformly transparent and wet, squeegee any excess epoxy off the top of the sample.

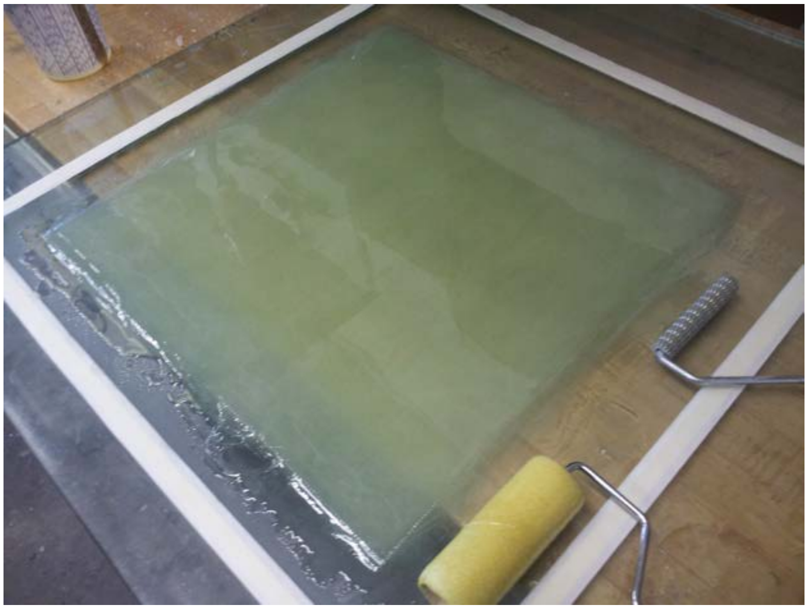

Figure 2. Sample After Epoxy Applied

e. Step 5: Vacuum

- Place the perforated release film on top of the sample.
- Place the foam on top of the release film. This will absorb any excess epoxy.
- Remove the backing to the sealant tape.
- Place the spiral hose along the top of the sample, connecting it to the vacuum hose.
- Place the vacuum bag over the foam and sealant tape, ensuring there are no wrinkles when it is bonded to the sealant tape. Extra care will need to be taken where the vacuum hose crosses the sealant tape. There will need to be additional sealant tape applied around the vacuum hose to ensure an airtight fit.
- Turn on the vacuum and apply 10 mm HG of vacuum for approximately five minutes. This is to ensure a negative pressure in the vacuum bag and remove any excess epoxy from the top of the sample. Using the vacuum for a longer period of time may result in epoxy being pulled out of the sample, leaving dry patches (See Figure 3).

Figure 3. Dry Patches Due to Vacuum

f. Step 6: Curing

Allow sample to cure at room temperature for a minimum of 24 hours.

2. Beam Sample

Follow the same steps as with the plate sample. For all intents and purposes, a large plate is created (see Figure 4). After curing, this plate is cut into multiple strips that can used to replicate a beam.

Figure 4. Beam Sample Prior to Cutting into Strips

C. STRAIN GAGES

1. Plate Sample

a. Orientation

A grid is drawn in one quadrant of the plate sample. Each quadrant measures 15.24 cm x 15.24 cm with the center corner being the point of impact when the sample is set in the rig. The quadrant is then divided into sections, with each section measuring 3.81 cm x 3.81 cm. A strain gage is place at the corners of these sections as seen in Figure 5. Due to being limited to only 15 channels of data, only 15 strain gages could be used. Each plate sample had seven tee rosettes and one linear gage for a total of 15 inputs.

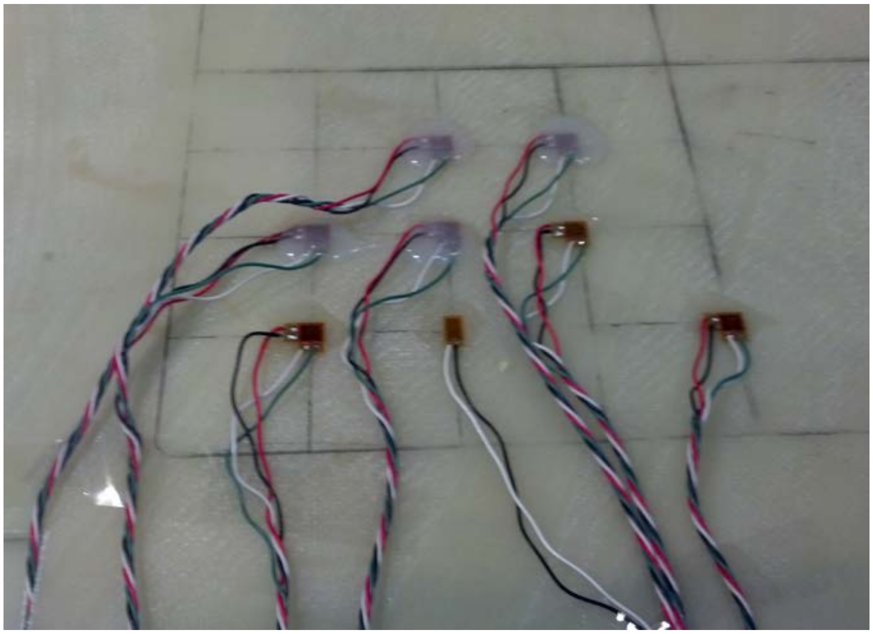

Figure 5. Strain Gage Orientation on the Plate Sample

b. Procedure

(1) Step 1: Preparing Surface. With a pencil, draw all measurements on the sample. Creating a 2-D grid is beneficial to ensuring the gages are straight.

Sand each area that will have a gage affixed with a fine sandpaper. Although the pencil marks will be removed, the lines that continue through will act as a guide when attaching the gages (see Figure 5).

Wash all residual dust off the sample with a lint free cloth and acetone.

(2) Step 2: Taping the Strain Gages. Using a small pair of pliers, arrange the strain gage on the sample in the desired placement and direction.

Using a piece of scotch tape, tape the strain gage to the sample at a 45° angle. This will allow the tape to be pulled up after curing at a 45° angle and eliminate some possibility of delamination.

Untape one side of the strip of scotch tape and wrap it over itself, so the strain gage is perpendicular to the sample and the tape is looped (See Figure 6).

Figure 6. Taped Strain Gages, Prior to Being Affixed to Sample.

(3) Step 3. Bonding Agent. Use M-Bond AE-10 adhesive kit (manufactured by Micro-Measurements) to bond the strain gage to the sample. This is a two part epoxy with a mixing time of 5 minutes. There is only a 15 minute working time for the AE-10, so the sample must be completely prepped ahead of time.

Apply a small amount of AE-10 to the sample, along one edge of the strain gage. A single droplet is almost too much of the strain gages, so care must be taken to minimize excess.

Untape the looped tape and slowly roll the strain gage back onto the sample, applying firm, even pressure to the gage throughout the process.

(4) Step 5: Curing. Put a small weight on each strain gage to ensure positive contact with the AE-10 and the sample. Figure 7 shows the curing step with a weight on each strain gage. Cure time should be a minimum of 48 hours.

Figure 7. Sample with Strain Gages Attached and Weights on Each Gage

(5) Step 6: Soldering Leads and Waterproofing. Once the strain gages are fully bonded to the sample, remove the tape and with a small blade, remove any excess AE-10 from the tabs of the gages. Solder wire leads to each tab, taking care to not overheat or burn the gage (See Figure 8).

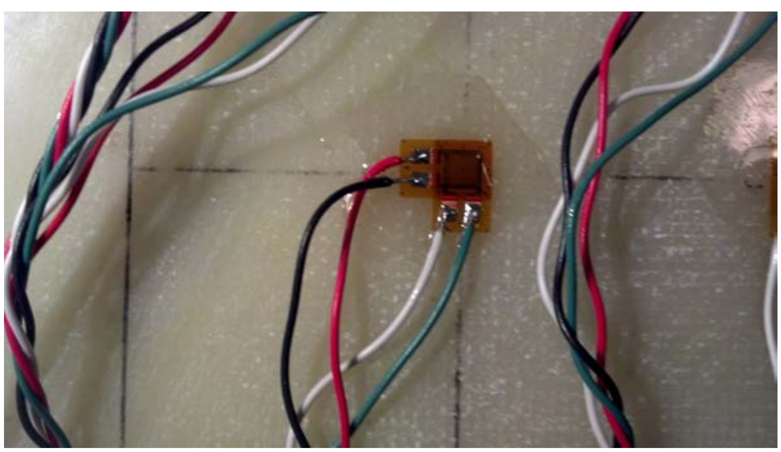

Figure 8. Soldered Leads on Tee Rosette Strain Gage

Apply the first coat of waterproofing material, M-Coat A (air-drying polyurethane coating)

This should cure for an additional 48 hours.

(6) Step 7: Apply Final Waterproofing Material. After the first coat is fully cured, apply a generous amount of RTV coating (MIL-A-46146) to the sample, ensuring all exposed leads and the strain gage are covered (see Figure 9).

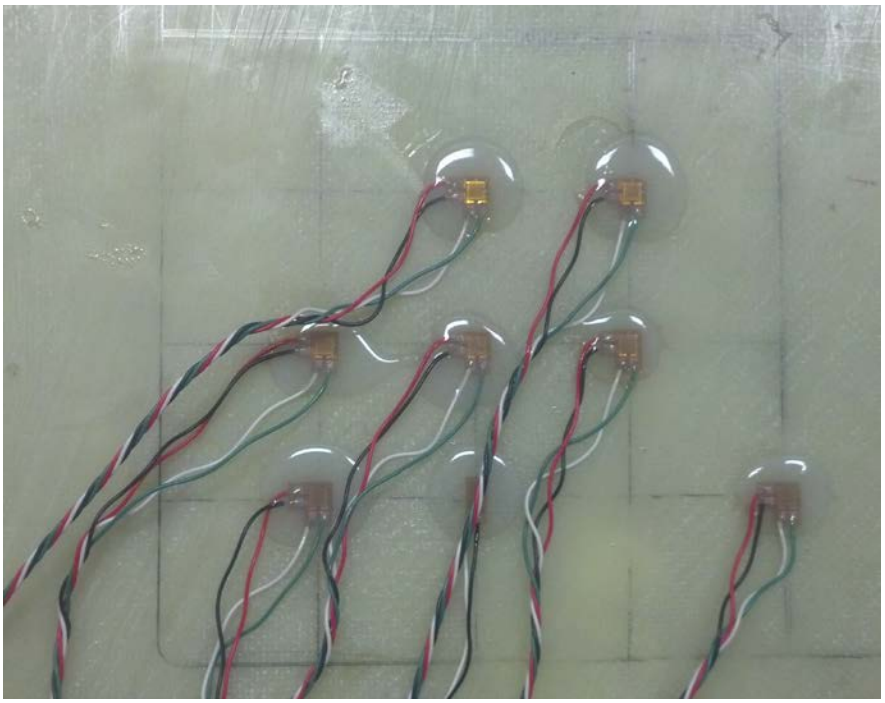

Figure 9. Strain Gages Fully Attached and Waterproofed.

2. Beam Sample

a. Orientation

The point of impact is determined on the beam. Starting 1.27 cm from the impact point, a strain gage is bonded to the beam. Five more linear strain gages are bonded to the beam, spaced 2.54 cm from each other. The same pattern is repeated on the other side of the impact point, with the initial spacing at 2.54 cm vice 1.27 cm (see Figure 9).

Figure 10. Beam Strain Gage Orientation

b. Procedure

The procedures for bonding strain gages to a beam sample are the same as the plate sample.

D. TEST RIG

1. Drop Weight Test Rig

A low velocity impact test rig had been built for a previous study (see A.C. Owens for a detailed description of rig components [8]). The rig, pictured in Figure 9, has a drop weight that slides on rails and impacts the top metal plate which is connected to a rod with a load transducer on the end that impacts the sample. The rig is wired to accommodate up to 15 sensors, plus the load transducer. The sample is then clamped between two aluminum plates on all four sides. Both the height and the weight of the drop weight were adjusted to increase the impact force on the plate samples.

Once the sample was installed in the rig, and all the sensors were wired up, the rig was suspended inside an immersion tank (see Figures 11–13). The tank was drained for all air simulations, and then was filled with fresh water until the sample was submerged 7.62 cm for all submerged tests. This ensures the response of the rig will be the same for both cases, with the only difference in the experiment being the medium the rig is immersed in.

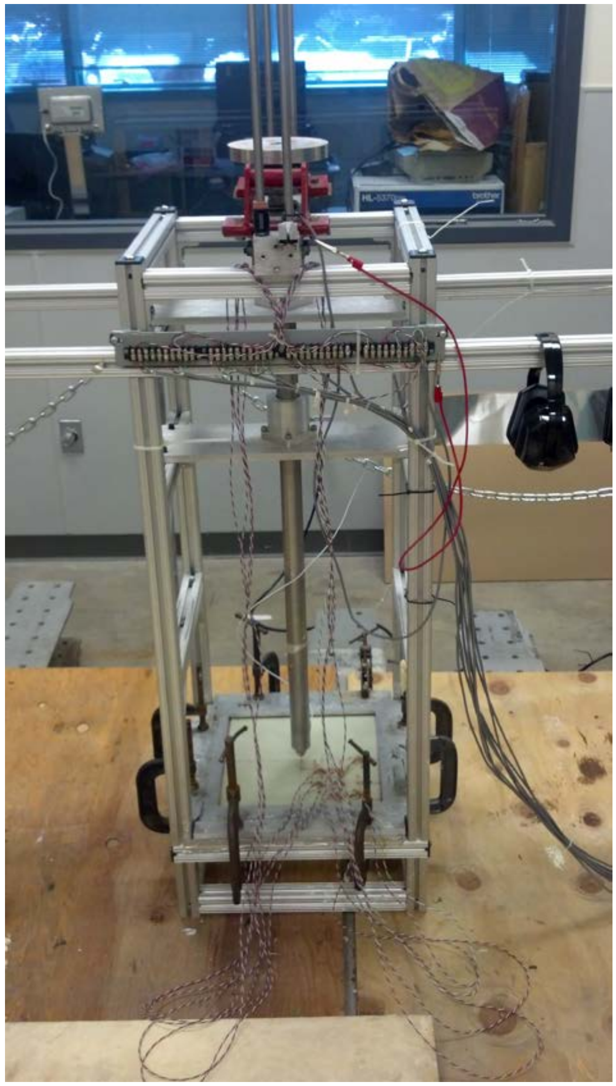

Figure 11. Test Rig, Configured for a Plate Sample

Figure 12. Test Rig Suspended Above Tank

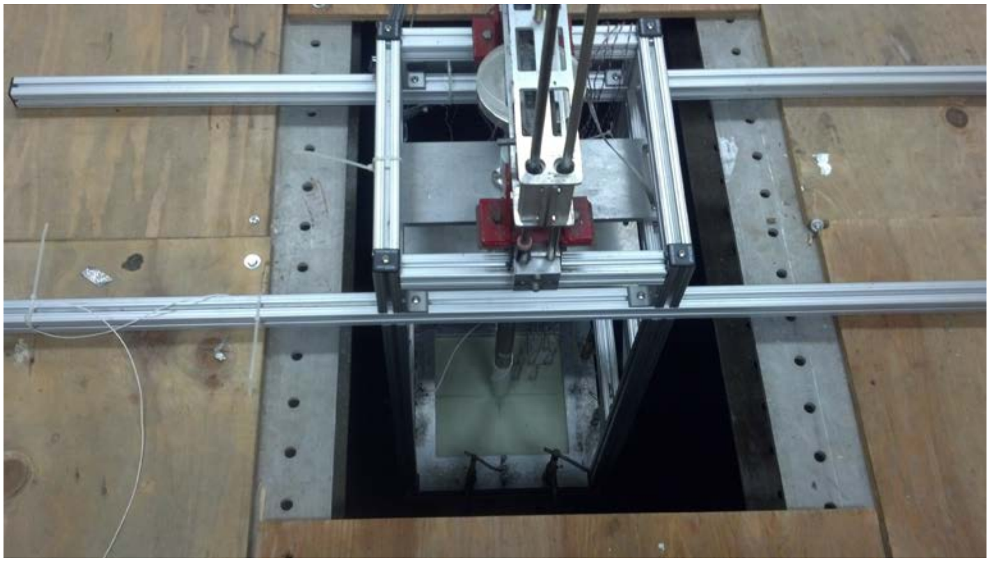

Figure 13. Test Rig in Tank, Ready for Data Acquisition

2. Plate Sample Data Acquisition

The plate sample was placed between two aluminum brackets and clamped with eight clamps (two per side). A water proof membrane was placed over the impact rod to protect the impact sensor from water intrusion.

The test rig had four thin plates attached to drop weight apparatus, with a total added weight of 4.63 kg. The drop weight was then lifted to a height of 50.8 cm and dropped a total of three times, and then again from a height of 76.2 cm for three runs. The tank was then filled with fresh water so that the sample was submerged 7.62 cm. The same heights were used for the submerged sample for a total of 12 runs.

Great care was taken to ensure the same conditions were experienced for both the air suspended and submerged data collection runs, with the only difference being the submerging of the sample into water.

Once the data for comparison was gathered, the drop weight was changed by removing two of the thin plates and adding a thick plate for a total added weight of 6.80 kg. The drop weight apparatus was then raised to a height of 50.8 cm and dropped three times, then 76.2 cm and dropped three times, and finally 101.6 cm and dropped until the sample broke or delaminated (between one and three strikes). Samples 10 and 12 were broken while submerged, and sample 13 was broken while suspended in air.

3. Beam Sample Data Acquisition

The beam sample was placed between two aluminum brackets, with an additional beam on either side to prevent the brackets from moving (see Figure 14) and clamped with six clamps (one clamp on each beam end). A water proof membrane was placed over the impact rod to protect the impact sensor from water intrusion.

The test rig did not have any plates added to the drop weight apparatus. This was due to previous trials with added weight resulting in a permanent deflected beam which needed to be reclamped after each trial. This meant that the impact point could differ slightly and the data could not be compared to previous runs (See Figure 13).

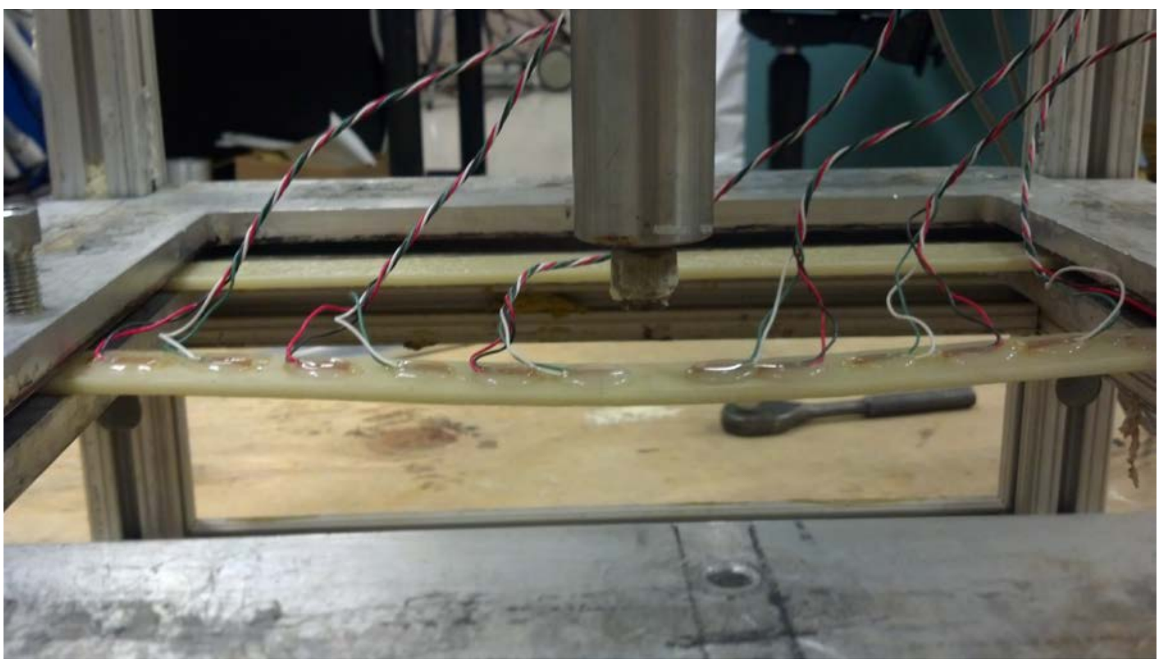

Figure 14. Beam Sample with Additional Plates Experiences Permanent Deflection

The drop weight apparatus was dropped from heights of 50.8, 76.2, and 101.6 centimeters, with three runs completed for each height. The sample was then submerged in 7.62 cm of water and the same drop heights were used.

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III. RESULTS AND ANALYSIS

Multiple plates and beams were tested under the same conditions described in Chapter II. When comparing the results between the various samples, the data was very similar both in magnitude and response. As such, only sample 13 (a plate sample) and sample 2 (a beam sample) will be closely analyzed in this paper to prevent redundant analysis. Within those samples, the various runs showed very similar results to the other runs with the same conditions (wet or dry, and drop height). This gives confidence to the fact that the differences between the various conditions are not just abnormalities because the results are verified between three individual runs for each sample, and between other samples with the same conditions.

For the purposes of this analysis, when the plate or beam is referred to as dry or wet, this is in reference to whether the sample is submerged in 7.62 cm of water or not.

A. SMOOTHING DATA

The data obtained from the sensors had a lot of noise in it. The raw data, which can be seen in Figure 15, has several rapid oscillations that can lead to a confusing plot. As time progressed, this noise was lessened by adding multiple grounds to the impact rig, as well as minimizing channel crosstalk during data gathering. To aid with data interpretation, a smoothing technique within Matlab was applied. The Loess method was used to smooth the data points and give a clear picture as to what is occurring with the strain gage, while minimizing channel cross talk and grounding faults. Figure 16 is the same raw data from Figure 15, but with the Loess method applied. The Loess method uses local regression by applying the weighted linear least squares. It also incorporates a second degree polynomial. The span that is examined can be adjusted, for these charts; a span of 10% was utilized.

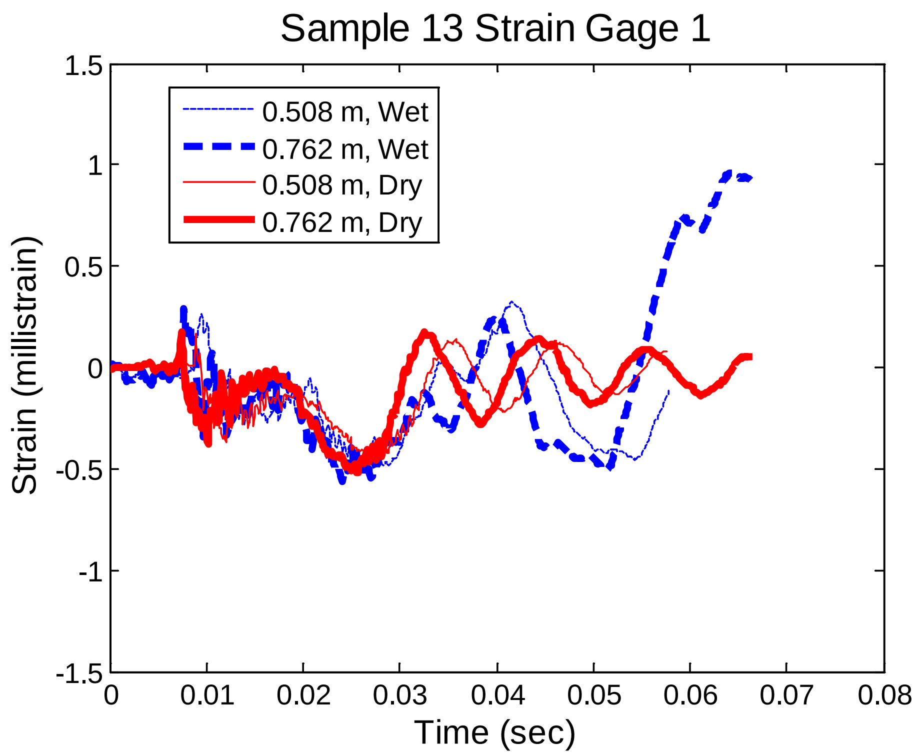

Figure 15. Strain Gage One, Raw Data (Plate)

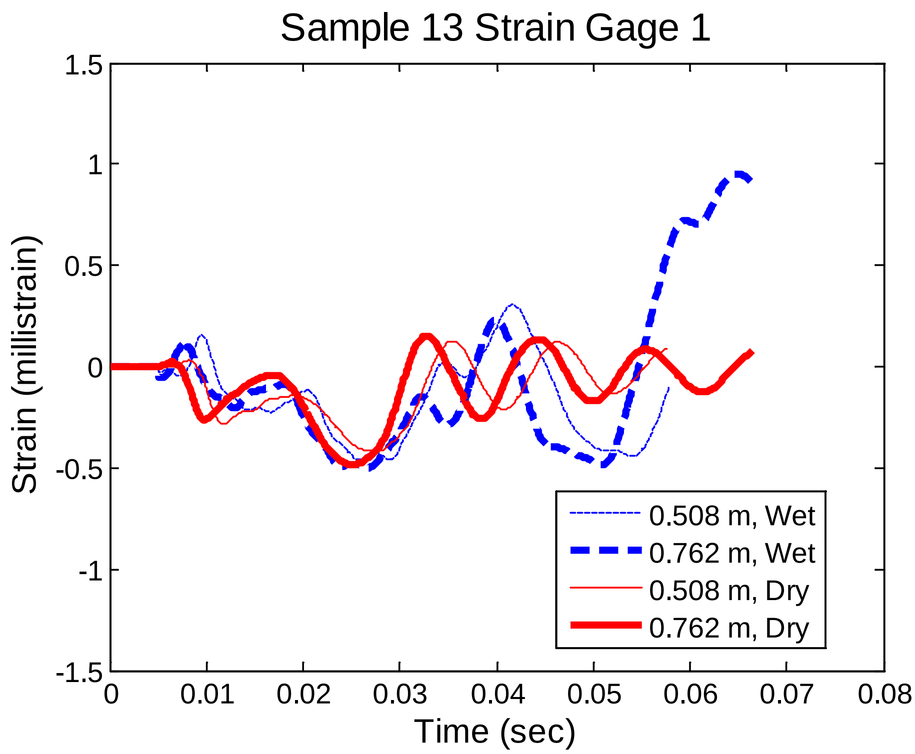

Figure 16. Strain Gage One, Smoothed Data (Plate)

B. IMPACT

1. Plate

The results from the force impacting the plate samples are very similar between the various runs and the plates. Figure 17 illustrates the response from the impact sensor for all twelve runs, three for each scenario (wet or dry for each impact rod drop height). The impacts are very similar between each of the three runs, and have similar trends for the increased height under the same conditions.

The data shows a very clear double peak for the wet impacts. At first, this can be reasoned that the impact rod rebounded after the initial strike and impacted the plate a second time. Upon observing this data, video was taken of both dry and wet impacts. The video was filmed at 120 fps and slowed to 12 fps, and clearly shows only one impact for the wet sample. The impact rod did not have a double strike on the plate. Of important note is the fact that the impact sensor was attached to the impact rod and was submerged for the duration of the wet impacts. There is not an impact with the surface of the water and then the plate.

Figure 18 is a comparison of the impacts from each of the four scenarios for plate impacts. The wet impacts had a noticeably higher impacting force than the dry impacts, as well as the double peak.

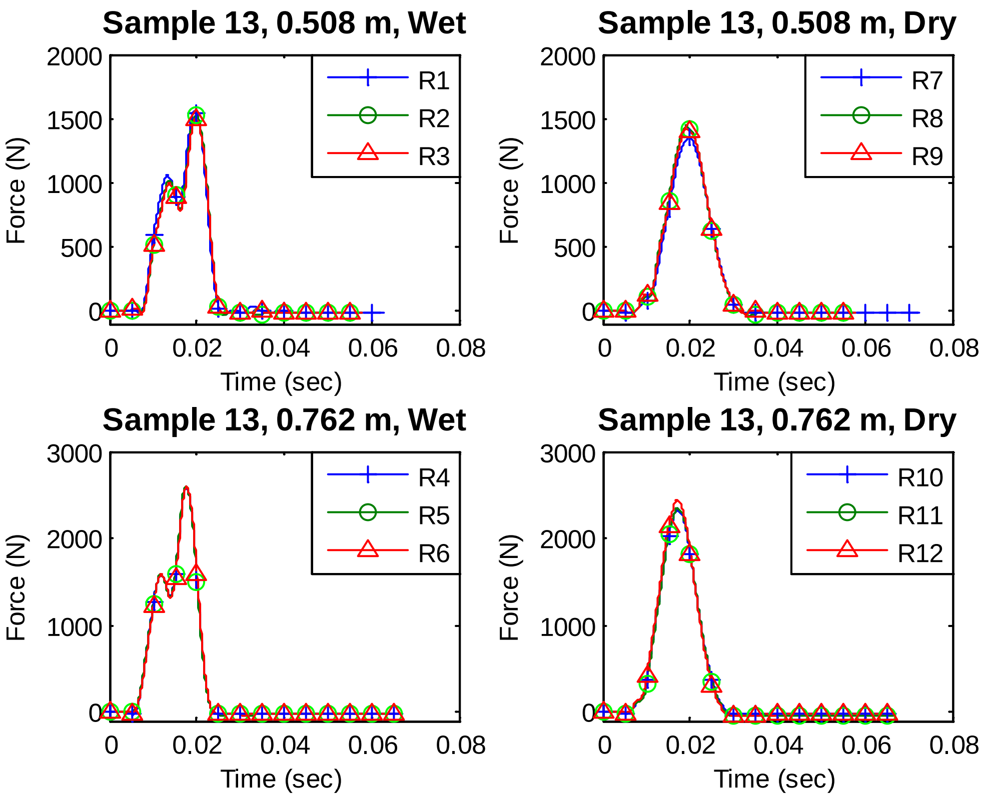

Figure 17. Sample 13 (Plate) Impact Data

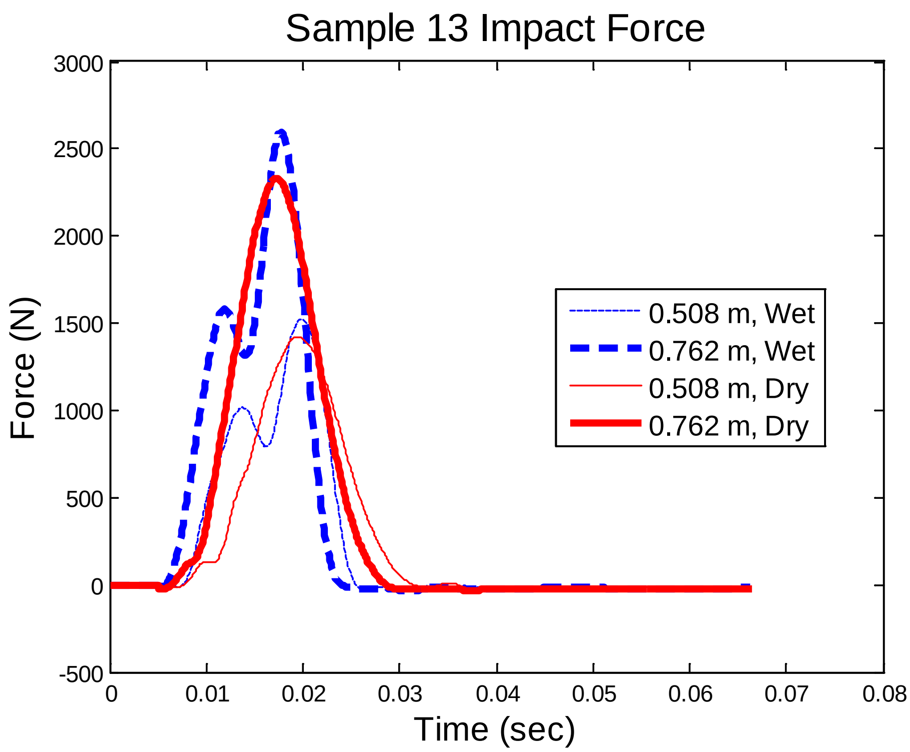

Figure 18. Sample 13 (Plate) Impact Comparison

2. Beam

The beam samples were impacted with less weight on them, and from varying heights. This was to prevent deflection after the first impact which would prevent subsequent impacts from being in the same location, which would skew the strain gage results. The data in Figure 19 shows slightly different trends than the plate samples. The wet impact seemed to oscillate throughout the impact period rather than having the clearly defined double peak previously discussed. Run 8 has a noticeably higher maximum than the other two runs, but this can be attributed to the drop height being slightly greater, or the weight not being released as quickly as the other runs.

A comparison between the various drop heights and wet versus dry conditions is offered in Figure 20. The impact force for the wet data is greater than the dry data, but the duration of time for both impacts are very similar.

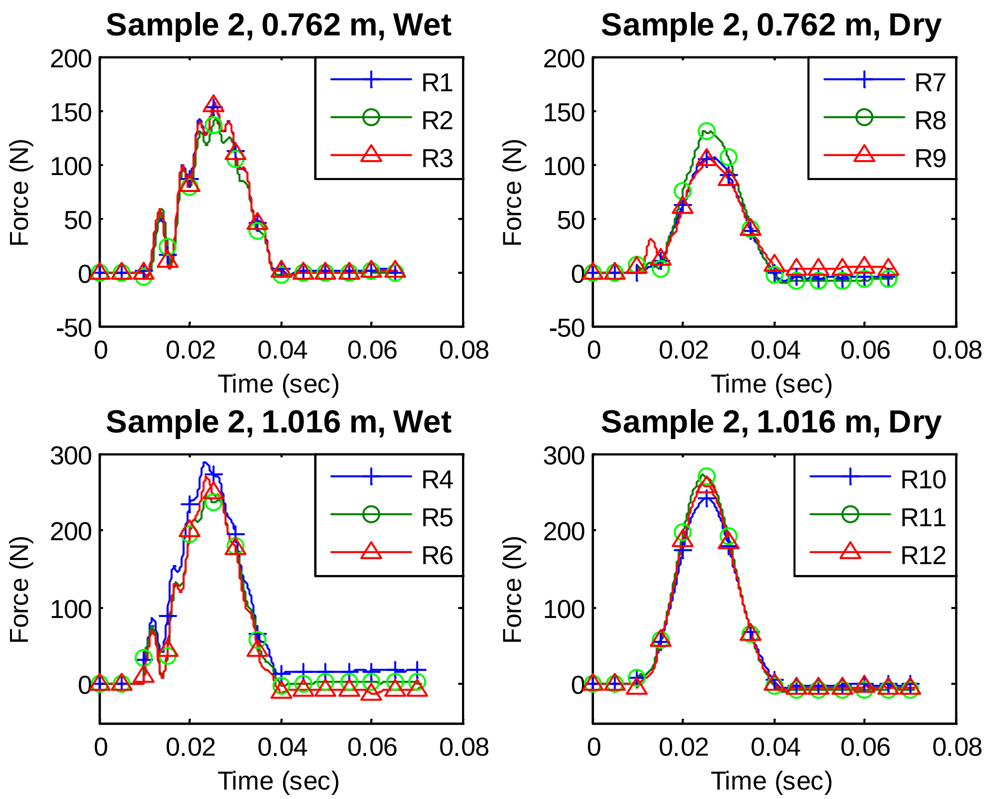

Figure 19. Sample 2 (Beam) Impact Data

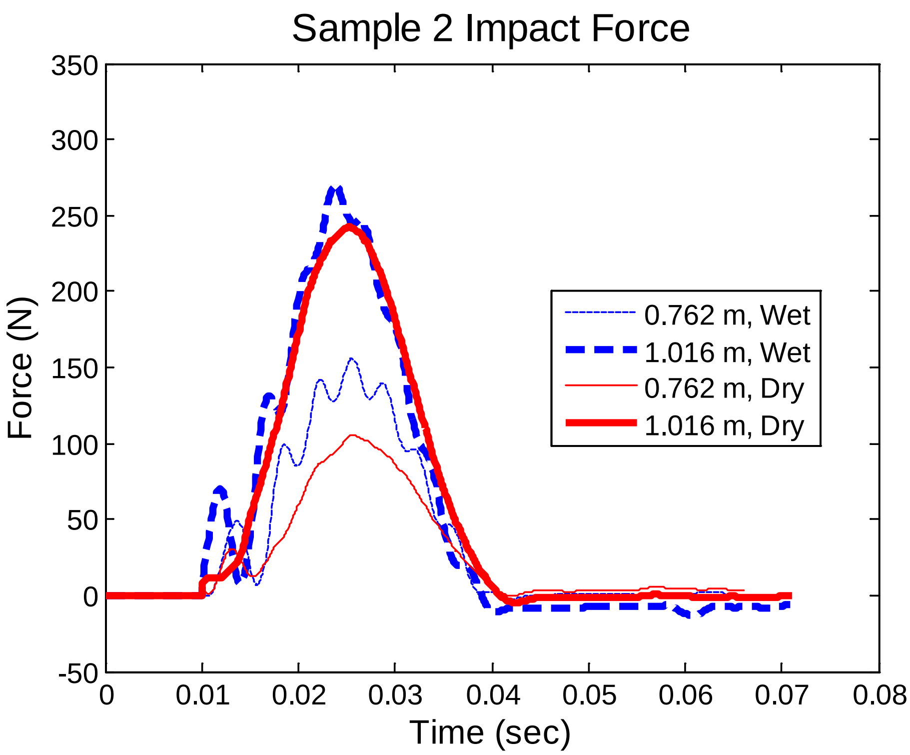

Figure 20. Sample 2 (Beam) Impact Comparison

C. PLATE RESPONSE

Each strain gage (SG) was assigned a number based upon which channel it was wired to. Figure 21 shows the nomenclature for the numbering of all plates. The point of impact is in the top left, and each grid is 3.81 x 3.81 cm.

The SGs show different responses depending on the location in correlation to the point of impact. Figure 22 shows the response of strain gage one (closest to the point of impact) and compares each of the three runs to the others of similar conditions (wet or dry, and drop height). The uniformity for all the data is also reflected in other plates and strain gages. Each of the 15 SGs has data that are in keeping with this figure and there is very little deviation between each of the three runs. The individual responses differ depending on location, and give a better story as to what is happening to the plate when it is submerged. The following figures, Figures 23 through 26, will compare the four different conditions to minimize the clutter on the graphs, but all data is uniform for each run.

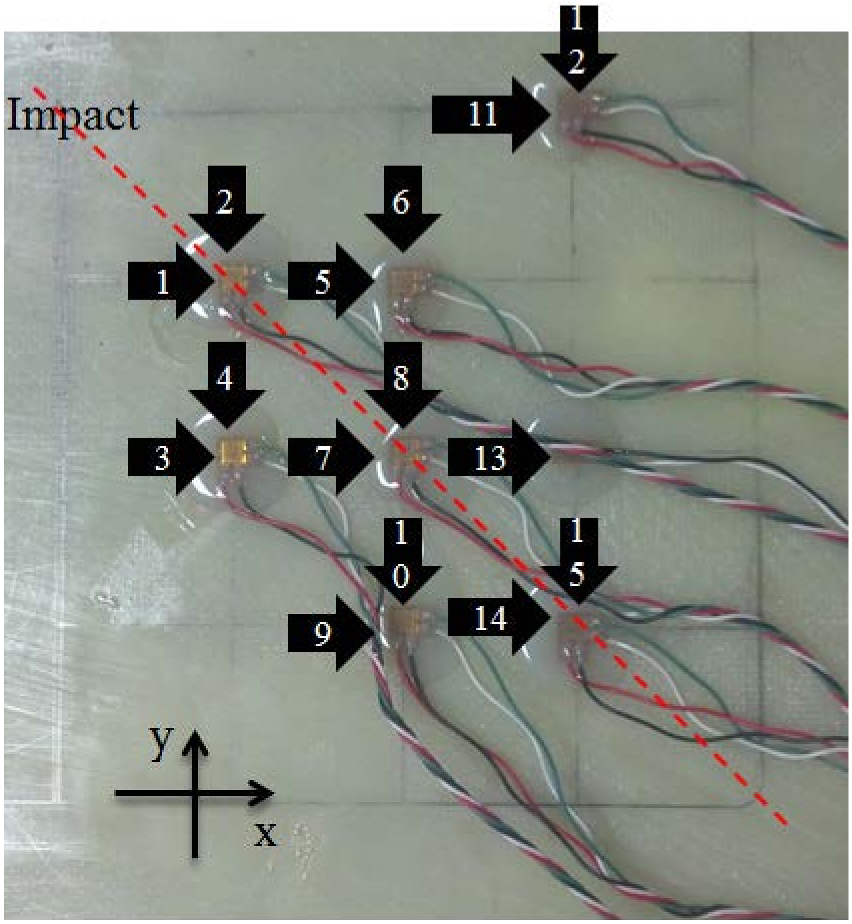

Figure 21. Strain Gage Numbering (Plate)

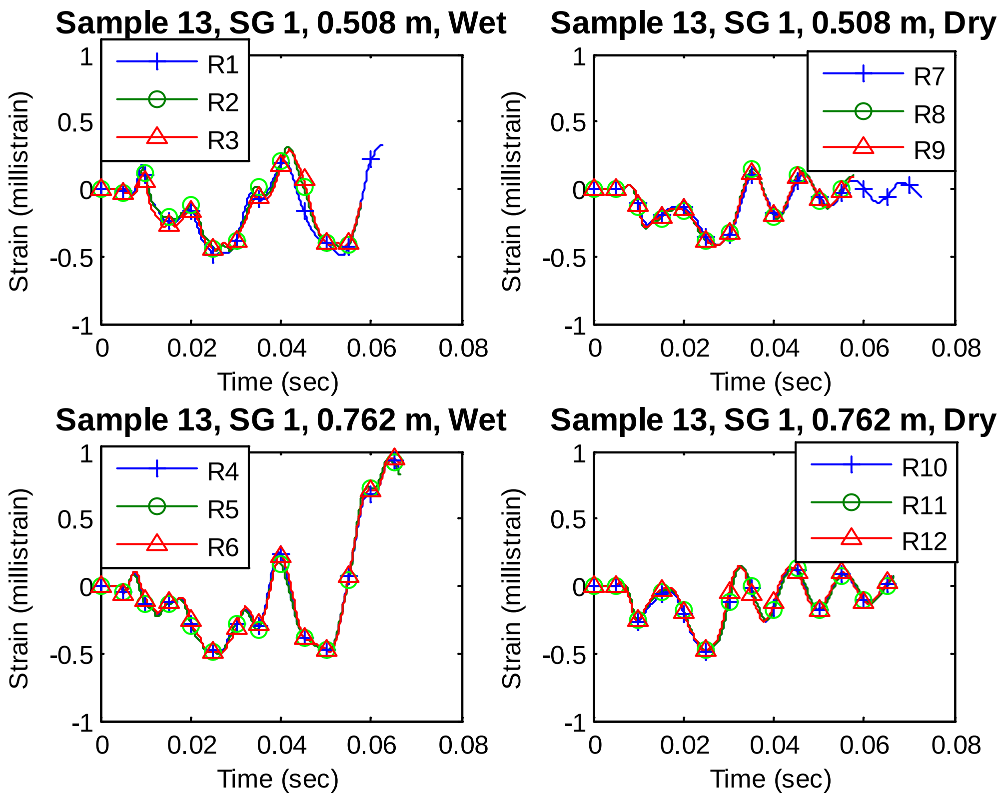

Figure 22. Strain Gage 1, All Runs (Plate)

When looking at the maximum strain experienced for each condition, SG 11 (Figure 26) shows the highest magnitude for the dry runs at 1.08 millistrains. The maximum magnitude for the wet runs is also at SG 11, at 1.48 millistrains. However, looking at the other gages, SG 5 shows a similar wet magnitude of 1.45 millistrains, despite the dry run only having a maximum of 0.62 millistrain (far less than the magnitude for SG 11 dry run). There appears to be a sudden shift of where the maximum strain is experienced when the plate is immersed in water and subsequently impacted.

Throughout the entire duration of the testing, the strain for the wet samples was more than the strain for dry samples. This difference was seen in the SGs that were not in the immediate vicinity of the impact (for example, SG 1 and 2), but rather those either in the middle of the plate, or closer to the boundary. SG 11 has a nearly 0.4millistrain difference between the wet response and the dry response for the maximum impact force.

It is also interesting that the SGs positioned in the middle of the plate have oscillations that increase at the end of the data gathering. However, the SGs along the clamped boundary edge (SG 11 for example), do not, and appear to have a dampened response.

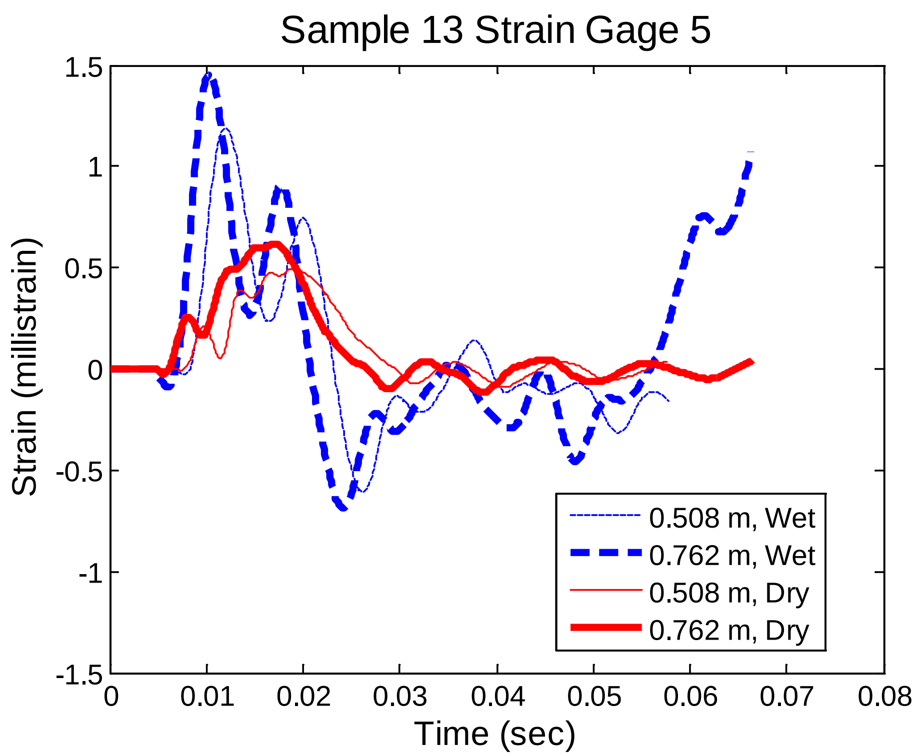

Figure 23. Strain Gage 5 (Plate)

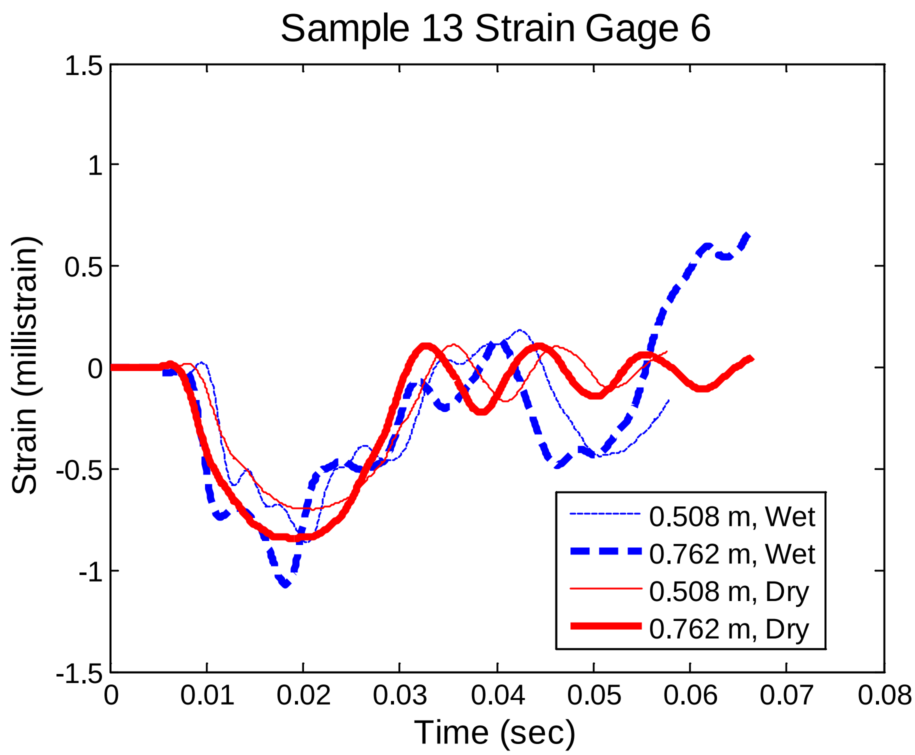

Figure 24. Strain Gage 6 (Plate)

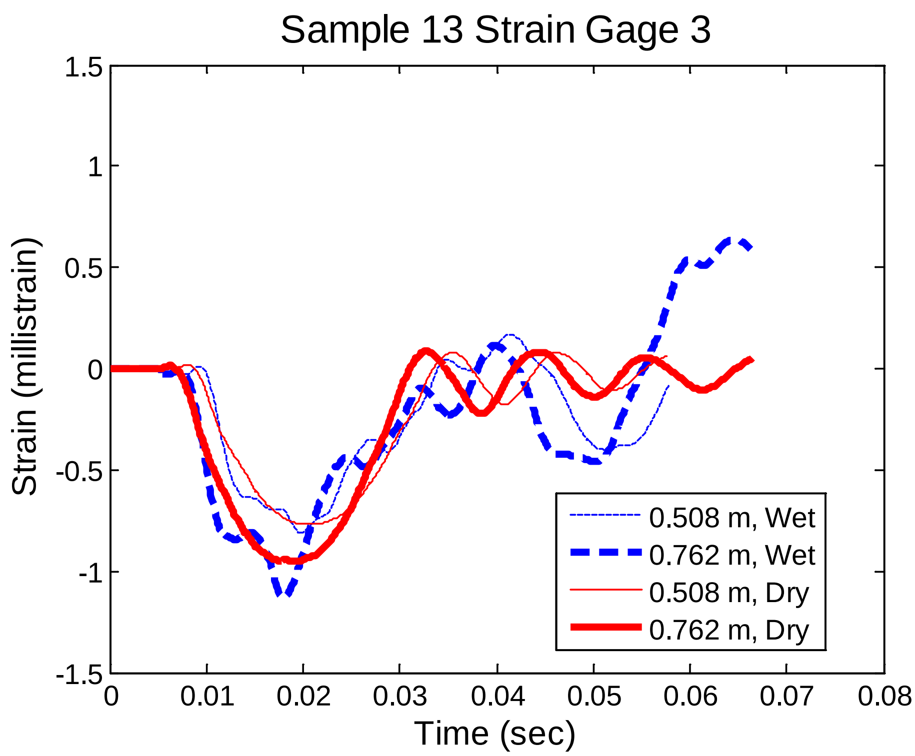

Figure 25. Strain Gage 3 (Plate)

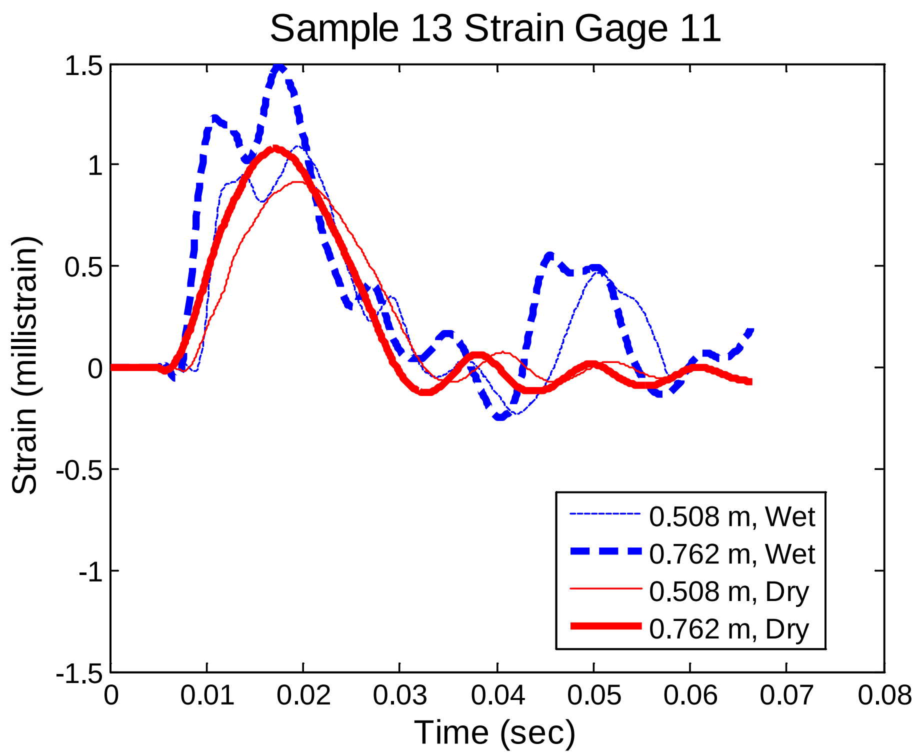

Figure 26. Strain Gage 11 (Plate)

D. BEAM RESPONSE

Each strain gage (SG) was assigned a number based upon which channel it was wired to. Figure 27 shows the nomenclature for the numbering of all beams. The point of impact is in the center. SG 6 is 1.27 cm from the impact, while SG 7 is 2.54 cm from impact. Each subsequent SG is 2.54 cm from the previous SG.

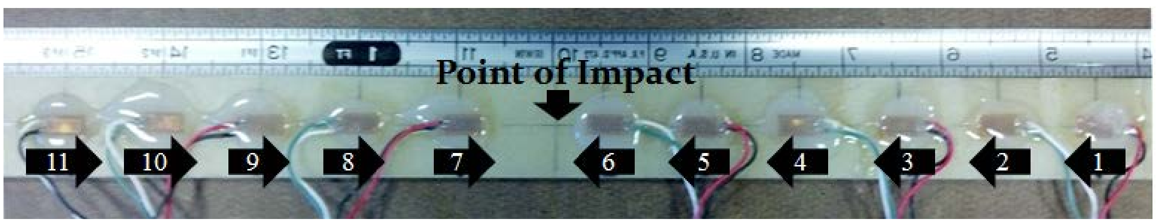

Figure 27. Strain Gage Numbering (Beam)

The strain gages show different responses depending on the location in correlation to the point of impact. Figure 28 shows the response of SG 6 (closest to the point of impact) and compares each of the three runs to the others of similar conditions (wet or dry, and drop height). The uniformity for all the data is also reflected in other beams and strain gages. Each of the 10 (11 were installed, but SG 1 had an error during testing and returned no data) SGs have data that are in keeping with this figure and there is very little deviation between each of the three runs. The individual responses differ depending on location, and give a better story as to what is happening to the beam when it is submerged. The following figures, Figures 29 through 34, will compare the four different conditions to minimize the clutter on the graphs, but all data is uniform for each run.

The beam response was similar to what is expected for a homogeneous beam that is clamped at both ends, with a loading in the center. The middle of the beam is concave up, and at some point, the concavity is swapped and the beam is concave down at the boundary. The strain results similarly show this to be true in the testing. SG 7 (Figure 29) is in compression, which means the SG is being compressed. Since the SGs are mounted on top of the beam, the SG is thus being forced in the downward direction. Conversely, SG 11, closest to the clamped boundary, is in tension, which means the beam is stretching the SG, thus the concavity of the beam has switched directions at some point (see Figure 30). This point is found in the middle of the beam, between the point of impact and one of the clamped boundaries. It was symmetric for both sides. This change in concavities occurs close to SG 4 (See Figure 31). It is seen that the SG does not go into compression or tension during the impact period, but rather oscillates about zero millistrain. Moving only 1.27 cm further away, SG 9 (Figure 32) shows the beginnings of a defined tension curve during the duration of the impact.

The strain between the wet and dry runs are very similar, with no significant difference in magnitude or oscillation for the gages closest to the boundary or the impact. The wet runs do have a longer period than the dry runs. Unlike the plate sample, the beam does not have the sudden increase in strain at the end of the testing for the SGs furthest from the boundary.

Both SG 5 (Figure 33) and SG 8 (Figure 34) illustrate an interesting phenomenon. Unlike the other SGs that have a clear distinction between the various heights of impact, these two SGs show that during the duration of the impact, the maximum strain experienced is the same, regardless of whether the sample was wet or dry, or the impact force.

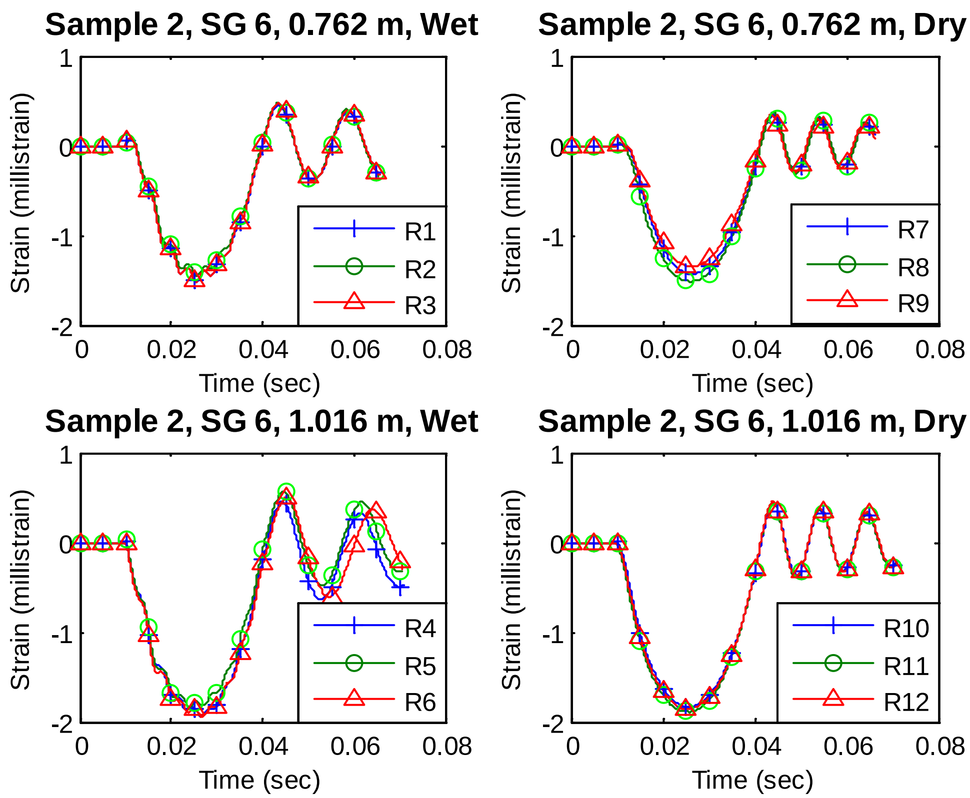

Figure 28. Strain Gage 6, All Runs

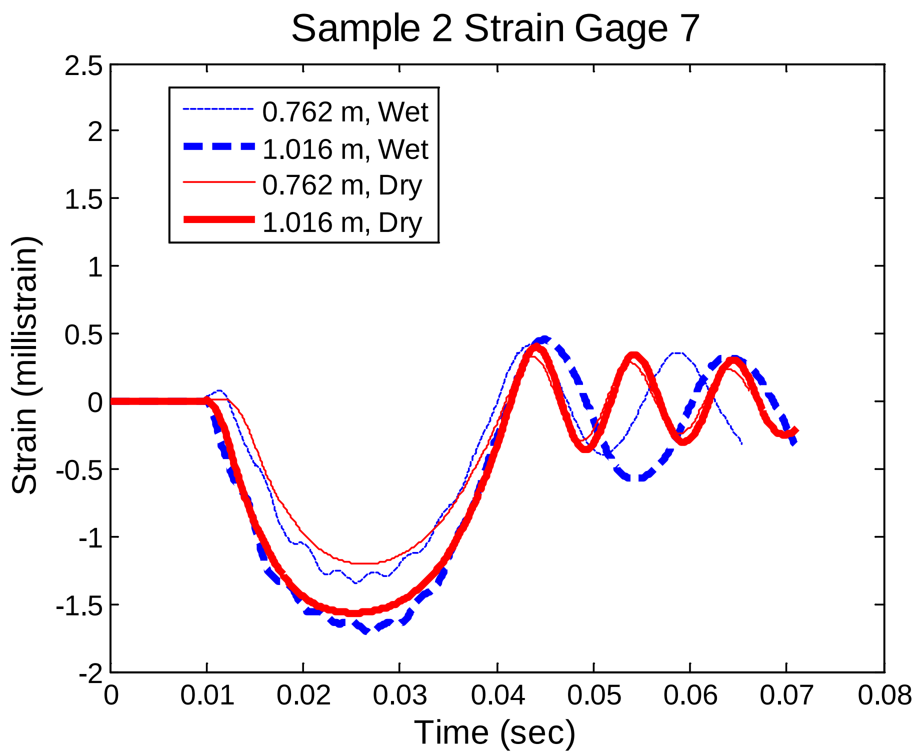

Figure 29. Strain Gage 7 (Beam)

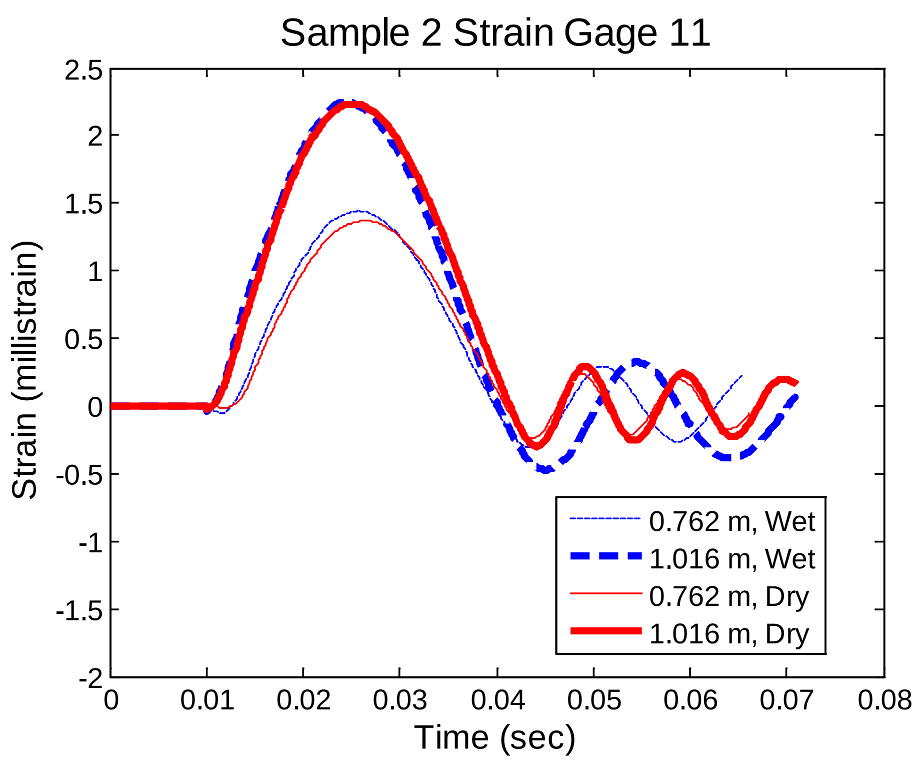

Figure 30. Strain Gage 11 (Beam)

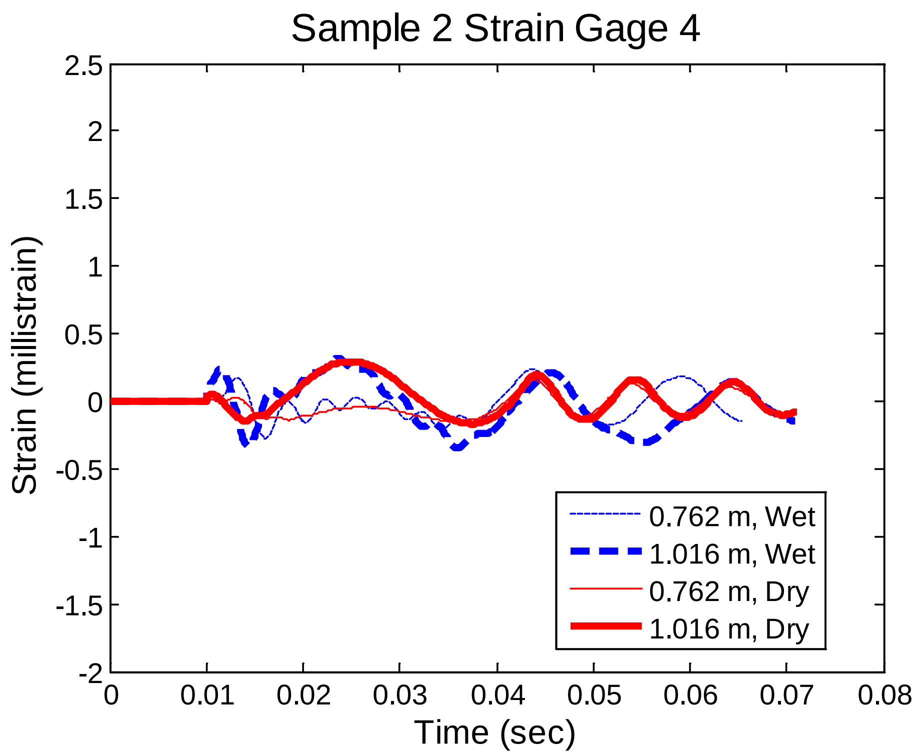

Figure 31. Strain Gage 4 (Beam)

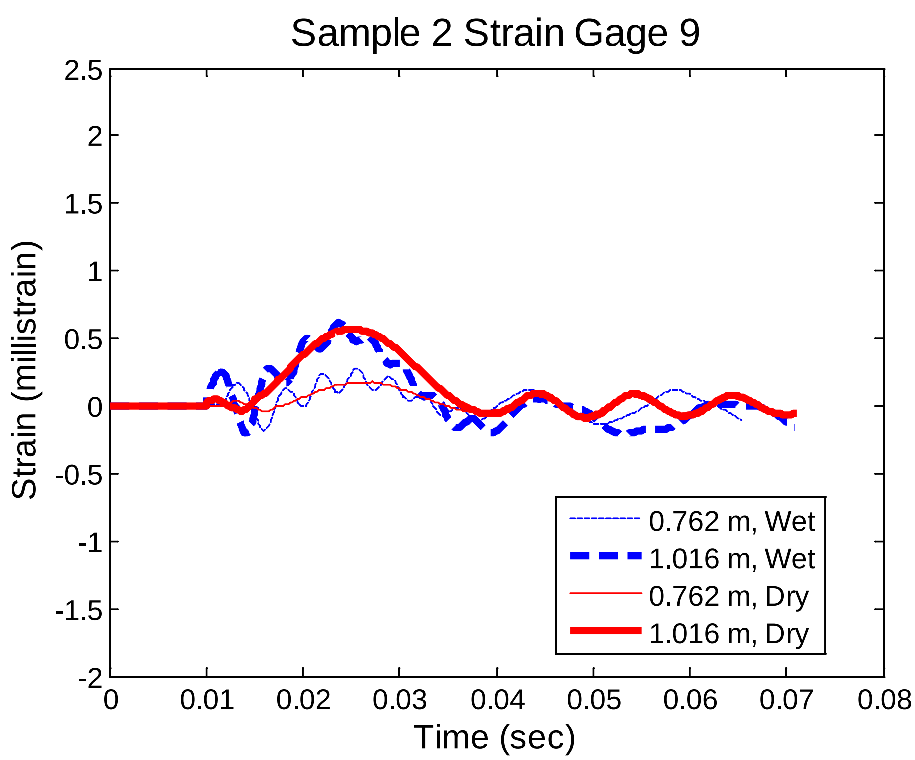

Figure 32. Strain Gage 9 (Beam)

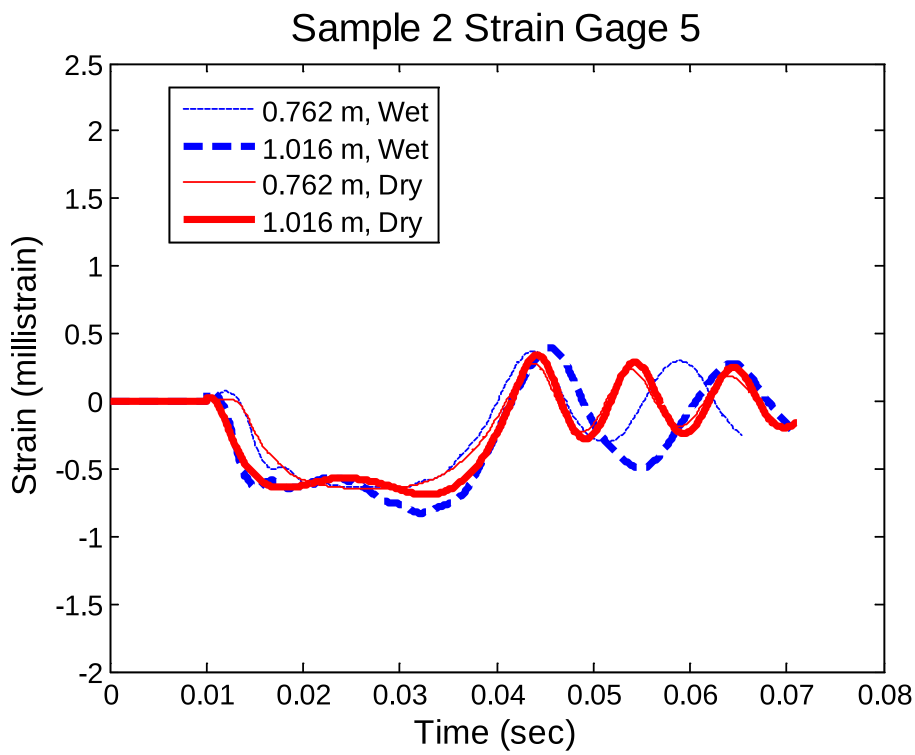

Figure 33. Strain Gage 5 (Beam)

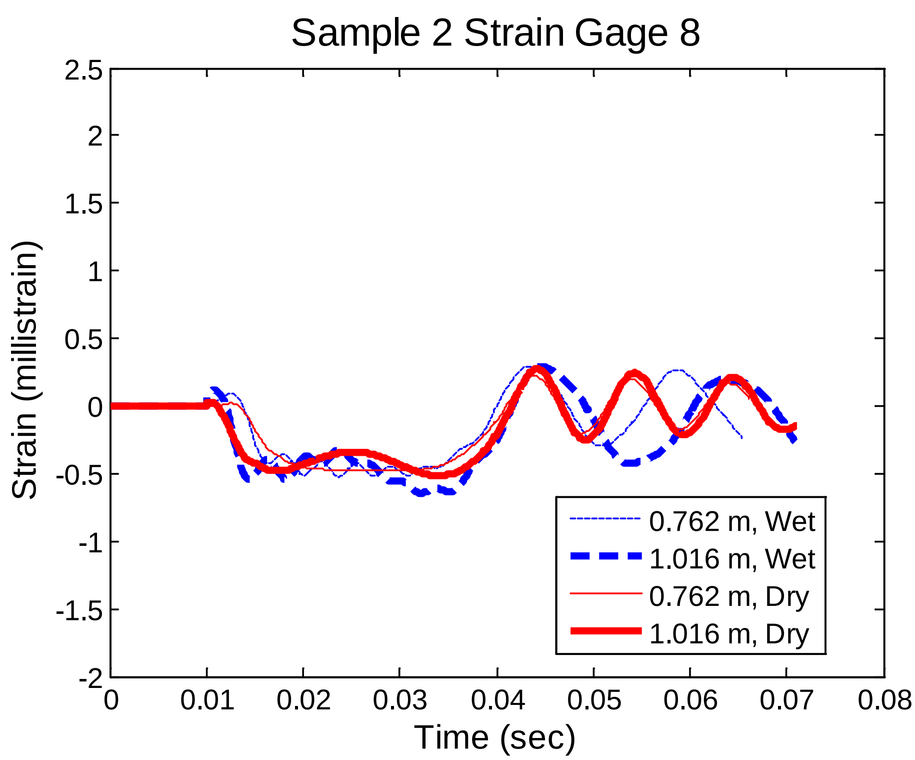

Figure 34. Strain Gage 8 (Beam)

E. BEAM COMPUTER MODEL

A computer model was developed in ANSYS to model the beam response under similar loading conditions. A beam was built in ANSYS that measured 30.48 cm x 2.54cm x 0.469 cm. The material properties included: Density = 2000 kg/m^3, Young's modulus = $20x10^9$ Pa, and Poisson's ratio = 0.3. Once the beam was modeled, water was added to the top of the beam, with a height of 7.62 cm and the same length and width of the beam. A second water column was added under the beam, with the same length and width, and a depth of 30.01cm (tank depth was reduced to minimize simulation time). Water columns were also designed to either side of the beam, which extended from the top of the column over the beam, to the bottom of the column under the beam (see Figure 35, beam is highlighted). The model geometry and engineering data was loaded into the "Transient Structural" analysis tool. The CFX tool "Fluid Flow" was then utilized to mesh the model and derive the results.

A point was inserted into "User Locations and Plots" using "Node Number" within the definition for the point. By moving the point along the beam by selecting different nodes, the results can be retrieved at the same locations that the strain gages were mounted. Lastly, a point impact force was added that was similar in magnitude to the experimental data impact of the beam. The model was then run and the desired data was viewed in CFD-post of the CFX tool.

The ANSYS model illustrates the changing concavity of the beam along its length (See Figure 36). The strain at the location that was equivalent to SG 7 was measured in the submerged state and the data was plotted against the actual run data (See Figure 37). The maximum strain experienced at that location is very similar for both scenarios. The differences can be attributed to a few known differences between the model and the actual data. One such fact is that ANSYS models a composite beam as a solid, rather than 18 layers built upon each other. This can detract from the flexibility of the beam, as seen after the end of the impact duration. Another difference is that the impact itself had to be modeled as a series of increasing forces, rather than a maximum strain applied at a single point in time. This was due to the water making the actual impact oscillate over time.

The strain after the time of impact dampens quickly and does not continue to oscillate like the experimental data does. This needs to be looked into further as to why the computer model has so much damping post-impact.

Despite these differences, the computer simulation showed that with a more in depth analysis, the data can be modeled and simulated. The computer simulation can give a better insight into why the beam responses were relatively similar, and yet the plate responses were vastly different between the wet and dry impacts.

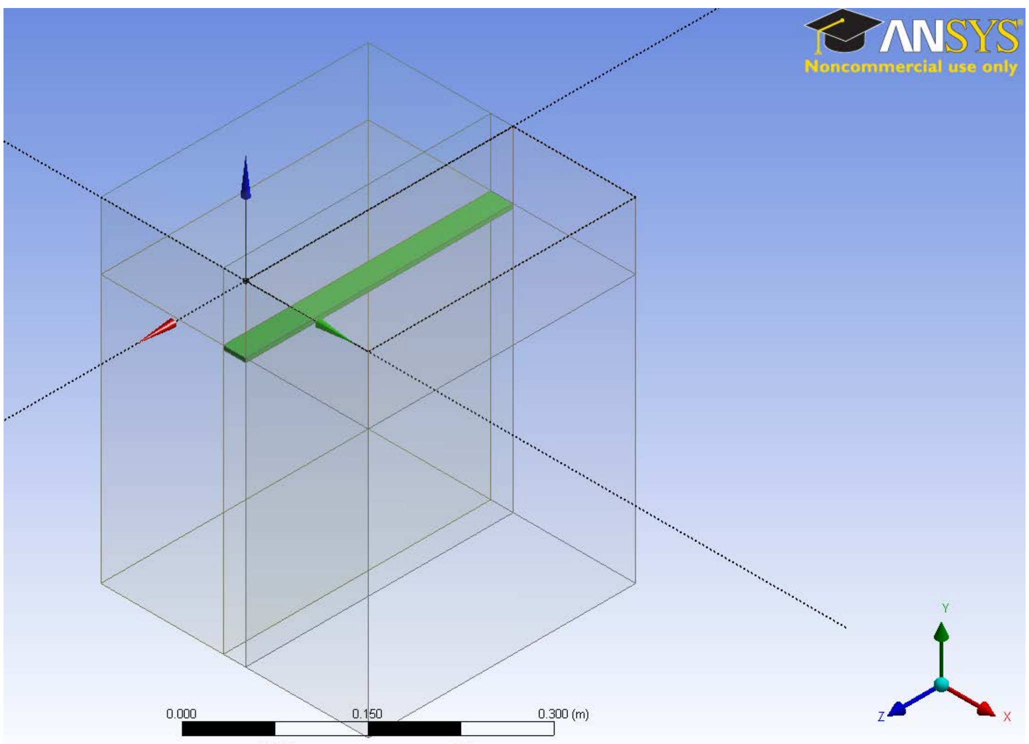

Figure 35. Beam Model Design

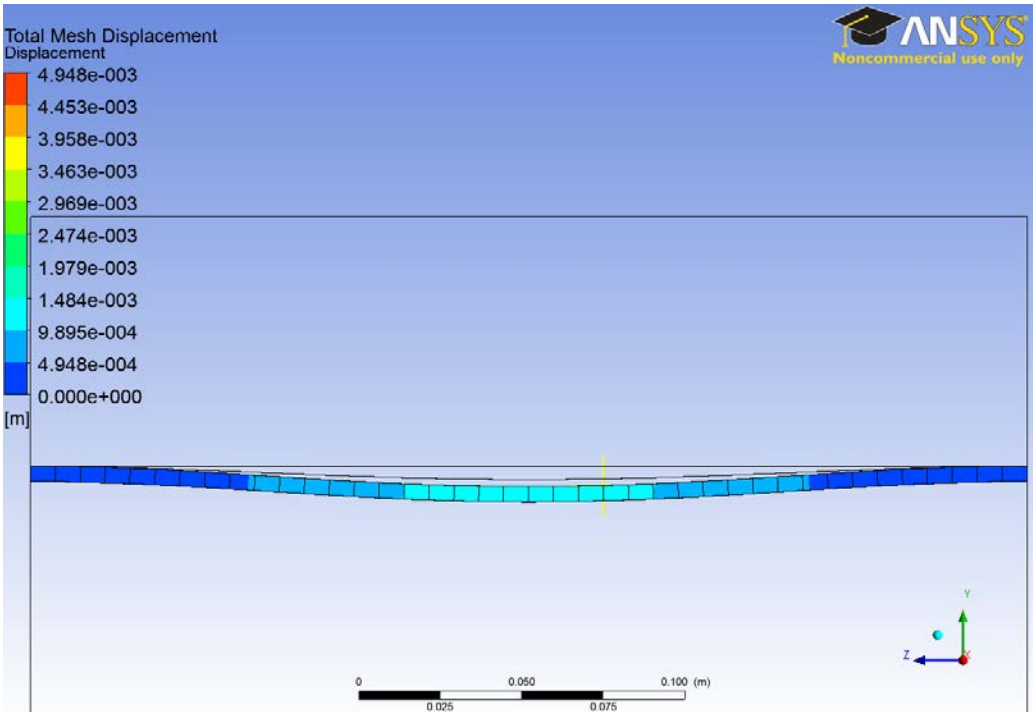

Figure 36. ANSYS Beam Displacement

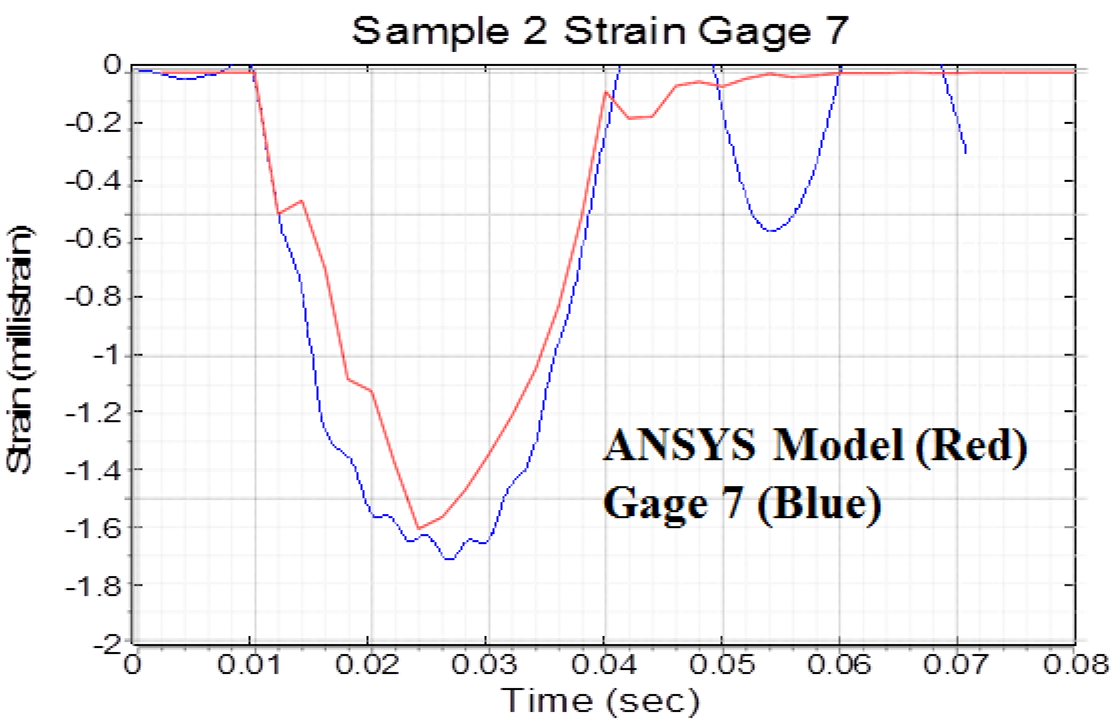

Figure 37. ANSYS Results Overlaying Strain Gage Results

IV. CONCLUSIONS AND RECOMMENDATIONS

A. CONCLUSIONS

For the plate sample, the wet response was very different than the dry response. The impact force was greater for the wet impact, and this did not have a linear correlation to the lesser force impacts. Additionally, the wet samples have the double peak impact, which can alter the response of the plate when submerged.

The largest increase in strain was at strain gage five. This showed a 2.4x increase from the dry condition testing. This increase also attributed to a shift in the maximum strain experienced in the sample. For the dry conditions, the max strain was experienced at strain gage 11. The wet response was also the maximum response at this location. However, strain gage five, despite have a lesser dry strain response, had a very similar max wet strain response. When the plate is submerged, the strain is shifting in max location and thus the concentration is different than the dry scenario. This can lead to fatigue in a location that the component would not normally display the first signs of fatigue.

The wet response was not only different in magnitude, but it was also different in shape. As time progressed, the wet impacts resulted in a larger strain at locations away from the boundary conditions. This larger strain surpassed previous magnitudes experienced immediately after the impact. The fact that this increase was not experienced for the dry plates gives concern to the design of components that have only been tested in a medium of air.

This testing proved that the plate responded like a homogenous and isotropic plate. This is proven by the fact that the strain gages that were located on the diagonal symmetric axis were similar in both the X and Y directions, while the strain gages off axis were similar to their counterparts on the other side of the axis.

The beam sample responded as expected, and by comparing the strain at similar locations, validated the model and illustrated that these responses can be modeled. The model must account for the multiple layers used to build a composite sample, and must be similarly damped to the real world scenario.

The fluid structure interaction plays a significant role for composite materials. With air as a medium, a conservative estimate can be developed as to what an expected strain will be. However, when that medium is changed to water, the added mass effect plays an important role not only for the impact force, but also in the response of the plate as time progresses. The immediate strain at the time of impact is increased, but there are also increases as time progresses after the impact. It is this continuing oscillations and changes in magnitude that can fatigue a component submerged in water, faster than a similar component surrounded by air.

B. RECOMMENDATIONS

Furthering the computer model is strongly recommended. A rudimentary beam model already illustrates the validity of the data, but more can be gained by utilizing a finite element approach to modeling the plate. This model will allow the end user to verify strain at any location, rather than only where a strain gage is affixed.

Further testing is needed for the plate sample. The time duration needs to be increased to better understand the sudden increase in strain after the impact is over. Additionally, the location of the strain gages should be adjusted to better examine the plate as a whole. With the knowledge that the plate response is homogenous and isotropic, only half the gages need to be used. This will allow for a larger area to be tested, or a more in depth examination of a smaller area.

The depth of the plate should also be adjusted. The results from various depths should be compiled and a better understanding of how water dampens the laminate response can be developed. This will prove useful for larger components that will be submerged at varying depths (i.e., a submersible).

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